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Energy valorization of industrial biomass: Using a batch frying process for sewage sludge

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ABSTRACT

This paper studies the energy valorization of sewage sludge using a batch fry–drying process. Drying processes was carried out by emerging the cylindrical samples of the sewage sludge in the preheated recycled cooking oil. Experimental frying curves for different conditions were determined. Calorific values for the fried sewage sludge were hence determined to be around 24 MJ kg^{-1}, showing the auto-combustion potential of the fried sludge. A one-dimensional model allowing for the prediction of the water removal during frying was developed. Another water replacement model for oil intake in the fried sewage sludge was also developed. Typical frying curves were obtained and validated against the experimental data.

1. Introduction

Sewage sludge is formed during wastewater treatment plant (WWTP) operations. The production of sludge available for disposal depends therefore on the financial, environmental and technological limitation of the given city or country (Werther and Ogada, 1999). In Europe, several pieces of legislation such as The Urban Waste Water Directive 91/271/EEC (Council Directive, 1991) impose a series of secondary treatment of wastewater in order to improve the aqueous environment. Indeed, the production of sludge has not stopped increasing. The amount generated annually is around 6900 million dry tons in the European Union (Catallo and Comeaux, 2008). Sludge may contain a high concentration of organic pollutant and toxic metal (EPA, 1979). It is disposed of for safety and environmental reasons or is recycled. However, recycling and reuse of sludge present a serious challenge because of its heterogeneous nature. The nutriment content of nitrogen and phosphor has fertilizing properties, however, heavy metals can be harmful when assimilated into the human food chain (Fytili and Zabaniotou, 2008). Although, landfilling presents the major alternative in developed countries with approximately 40% in the European Union (Fytili and Zabaniotou, 2008; Werther and Ogada, 1999), this solution induces many uncertainness. One of the problems of landfilling is the unsteady physical and chemical nature of sludge, namely odors, gas emissions (CH_4) and leachate transport into neighboring subsoils. Some legislation proposes to establish typical standards for sludge in order to reduce the risks and to ensure protection of the ground water. In coastal areas, transport by boats and dumping in the deep sea are actions taken by some countries. Nevertheless, these activities are unsafe, as the seas cannot absorb unlimited quantities of waste (Fresenius, 1990). In addition, there is a risk of contamination of the maritime coast as sludge contains great quantities of pathogenic matter (Eljarrat et al., 2001).

It has been reported that thermal oxidation processes result in the best global warming balance from an energy perspective (Houillon and Jolliet, 2005). These processes involve thermal destruction of toxic organic compounds and provide a large volume reduction of about 30% after incineration (Malerius and Werther, 2003). The energy balance for a sludge combustion process can only be positive when the required energy for drying is less than the calorific value of the sludge.

In fact, incineration of sewage sludge requires additional energy during the thermal drying step as it contains a large volume of water (60–80%) (Werther and Ogada, 1999).

According to Furness et al. (2000), the solid content in the sludge should be considerably reinforced to be auto-thermal. For this, direct or indirect drying methods are often used nowadays. Afterwards, coal, oil, gas or dried sludge may be used (Tchobanoglous et al., 2003) to fuel the incineration process. The present work deals with an innovative technique for the thermal drying and conditioning of sludge by a fry–drying process. This process offers the possibility of valorization of two wastes: sewage sludge and recycled cooking oil combined into a solid fuel.

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2. The fry–drying concept

Frying, one of the oldest processes of the food industry consists of drying by contact with hot oil and involves simultaneous heat and mass transfer (Moreira et al., 1999). Knowledge of the heat and mass transfer rates during the frying process is essential in order to evaluate the quality of the final product such as calorific values, oil uptake, porosity changes, etc. While the frying of food products has been the subject of a large number of investigations (Baumann and Escher, 1995; Pedreschi and Moyano, 2005; Chen and Moreira, 1997; Ngadi et al., 1996; Totte et al., 1996), the literature concerning the frying of sewage sludge is scarce. Silva et al. (2005) used a commercial fryer with a capacity of 5 l using fresh and used oil. They introduced the cylindrical samples of sludge (20–26 mm diameter and 40 mm length) into the oil heated to 190 °C and 215 °C. Their methods resulted in a dried sludge with less than 5% moisture and 24 MJ/kg calorific value after 600 s of frying. Peregrina et al. (2006a, b) examined fry drying of municipal sewage sludge using recycled cooking oil. The experimental tests were carried out using a continuous method with on-line weight measuring at operating temperatures between 120 and 180 °C. These studies indicated that oil acts as a medium of heating and as a component of the final product that improves its calorific value.

The above studies provided important information about the physical mechanism that takes place in the fry drying of sewage sludge. However, moisture and oil transfer are still not understood. The simultaneous aspect of the thermal and mass transfer, and the change of the physical properties of the product with the temperature and moisture, makes the theoretical treatment more complicated. Several mathematical models were developed for frying of food material. The basic energy and mass equations are often the same. The difference between the models lies in the choice of the transport mechanisms, the reformulation of the medium, the boundary conditions and the physical properties. Farkas et al. (1996a, b) proposed a one-dimensional model, involving two regions in the fried material: the crust and core. The crust region was defined by two criteria: its temperature is higher than the boiling point and the concentration of liquid water is negligible. Heat is transmitted by conduction. Additionally, one component of the energy leaves the heart by advection. Each region is in a dynamic state during frying, the crust is becoming thicker and the core thickness is decreasing.

Yamsaengsung and Moreira (2002) used a multiphase porous media model. They considered six phases (liquid water, bound water, vapor, air, oil and solid matrix). The transport of the liquid phases (water and oil) was supposed to be controlled by two phenomena: (1) capillarity which depends on saturation of each phase and the temperature and (2) convection. Gas phase transport, was reported to be a result of convective flow and molecular diffusion. In each phase, convection was expressed by Darcy's law. Baik and Mittal (2005) developed a non-symmetric model without considering crust formation. The moisture was assumed to diffuse through the product by a gradient of concentration and boiling on the surface.

Fassano and Mancini (2007) presented a mathematical model for deep frying using a one-dimensional geometry assumption involving an inner zone saturated with liquid water followed by a region of pure vapor. The transport of the liquid was assumed to happen by diffusion with a constant diffusivity and by the pressure gradient in the vapor phase. In order to improve their approach, Fassano and Mancini (2008) reformulated their model by replacing the diffusive transport of liquid water by a Darcy's law including the effect of capillarity, and vapor permeability as a function of temperature.

3. Present model

3.1. The problem description and assumptions

The aim of this work is to study the main phenomena occurring during a fry–drying process. Two quantities change greatly during frying: moisture content indicating the water loss from the sewage sludge and oil content indicating the amount of oil that the sample uptakes during frying.

Cylindrical samples prepared from a modified syringe are placed in an oil heat bath. There is, however, a certain transfer of heat coupled to the mass transfer of the water and the oil. Heat is transferred from the surrounding oil to the product surface by convection and through the product by conduction. We assume that moisture inside the sludge diffuses to its surface due to concentration gradient then leaves the surface in the form of vapor at atmospheric pressure. Oil diffuses in the direction opposite to that of water. In addition, the following assumptions were made: (a) The sludge is initially considered isotropic and homogeneous. (b) The initial moisture is uniform. (c) Since the radial dimensions are much smaller than those along the axial length, an infinite cylinder model was assumed. (d) Moisture diffusion coefficient was assumed to be constant during frying but a function of the oil temperature and initial moisture. (e) The mass diffusion of oil in the fried material has a negligible effect on other mass fluxes (i.e. the rate of water removal).

3.2. Governing equation

The mathematical formulation may be simplified by considering axial symmetry of the sample. The governing differential equations describing moisture diffusion in the product during frying consider diffusion in the form of a Fick's law

$$\frac{\partial M}{\partial t} = \frac{\partial}{\partial r}\left(D_w \frac{\partial M}{\partial r}\right) \tag{1}$$

where M[% kg water by kg fried product] is the local moisture content, $D_w[\mathrm{m^2 s^{-1}}]$ is the moisture diffusion coefficient, t[s] is the frying time, and r[m] is the radius of cylindrical particle.

The relationship between the diffusion coefficient constant, oil temperature and initial moisture content was assumed in the form:

$$D_w = (aT_\infty + b)\exp\left(\frac{-(cT_\infty + d)}{T_\infty} + e\langle M_0\rangle\right) \tag{2}$$

where a, b, c, d and e are the correlation factors, $T_\infty[k]$ is the surrounding oil temperature, the operator $\langle\cdots\rangle$ denotes the volume average of the moisture content, and the subscript 0 denotes the initial value.

The mass transfer boundary condition for moisture is (Farkas et al., 1996a; Chen and Moreira, 1997):

$$\left.\frac{\partial M}{\partial r}\right|_{r=0} = 0 \tag{3}$$

At the surface of the product, moisture is in instantaneous equilibrium with oil (Ateba and Mittal, 1994). The boundary condition takes the form:

$$M(R,t) = \langle M_{eq}\rangle \tag{4}$$

where R[m] is the half thickness of the particle and the subscript eq denotes the equilibrium.

$\langle M_{eq}\rangle$ is the equilibrium moisture content determined from long term experiments and from calculation. Moreover, during calculation this parameter still not known until the end. Therefore, the experimental equilibrium moisture content is attributed to the